# Overview of C-2W: High Temperature, Steady-State Beam-Driven FRC Plasmas

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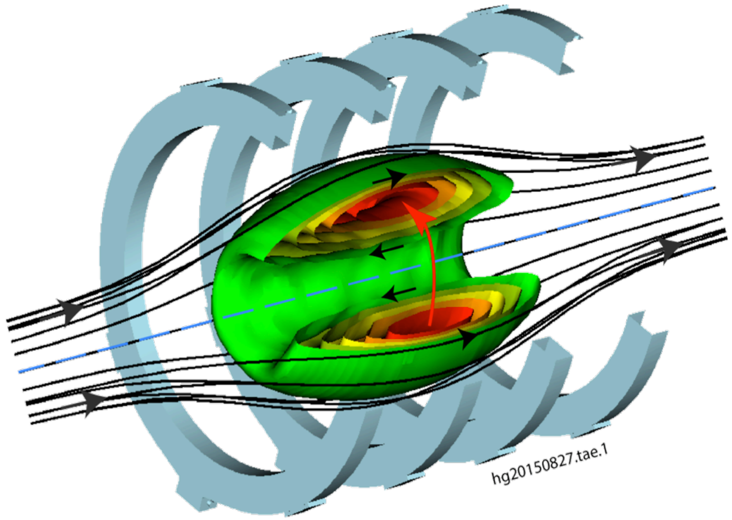
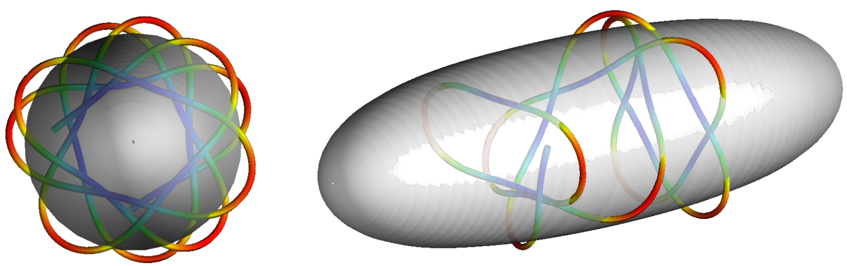
# Outline

- TAE’s Concept, Motivation and History
- Key Program Accomplishments
- Highlights of Experimental Results
- Summary

# TAE's concept – advanced beam-driven field-reversed configuration (FRC)




FRC: field-reversed configuration



Large orbit ions via Neutral Beam injection

- High plasma β ~ 1
  - Compact and high power density
  - Aneutronic fuel capability (e.g., p-$^{11}$B)
  - Indigenous large orbit particles
- Tangential Neutral Beam Injection
  - Large orbit ion population
  - Increased stability and reduced transport
- Easier design and maintenance due to simple geometry
- Linear unrestricted divertor facilitates power, ash, and impurity removal

# Key program accomplishments

- **Established beam-driven high-β FRC physics test bed with unmatched operating flexibility**
- **Demonstrated high-temperature FRC sustainment via neutral-beam injection and edge biasing**
  - FRC sustained up to 30 ms (limited by the energy storage on-site)
  - Achieved total plasma temperature > 3 keV
  - Extended operational boundary, S*/E > 3 (historical limit ~3)
- **Established collaboration with academia and industry to accelerate progress**
  - PPPL, UCI*, UCLA*, LLNL, ORNL, Univ. of Pisa (Italy), Univ. of Wisconsin, Nihon Univ.* (Japan), Budker Institute* (Russia), ASIPP (China), Google*, industrial partners, and more

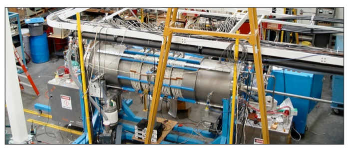
*Acknowledgement: co-author of this paper

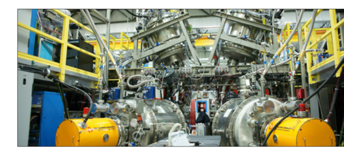
# Past progress

## From 2000 to 2016

- TAE has made substantial progress in technology and science
- Rapid pace with specific goal/milestone oriented





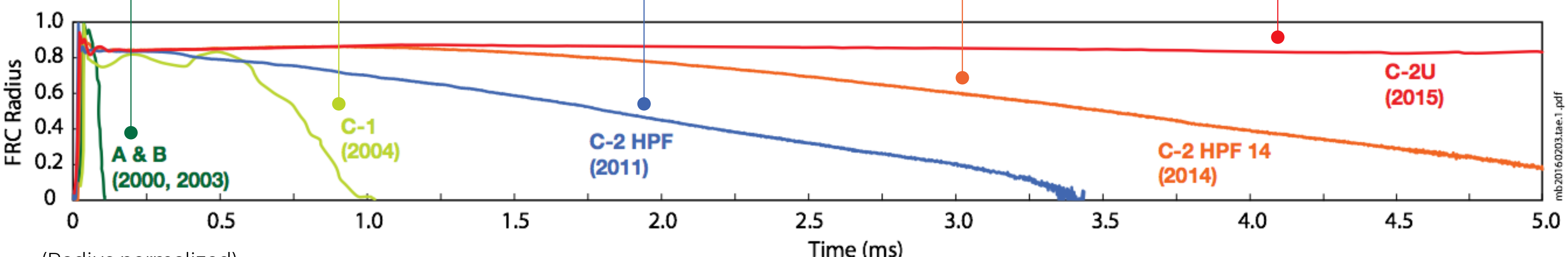
**A & B – Basic FRC core**
100-800 G, 5-10 eV
ion beams, $W_b$ ~0.1 kJ

**C-1 – Enhanced lifetime**
400 G, 10 eV
ion beams, Wb ~1 kJ

**C-2 – HPF* w/ 2 guns, Ti**
1 kG, 1 keV
neutral beams, Wb ~12 kJ

**C-2 – HPF* w/ 2 guns, Li**
1 kG, 1 keV
neutral beams, Wb ~20 kJ

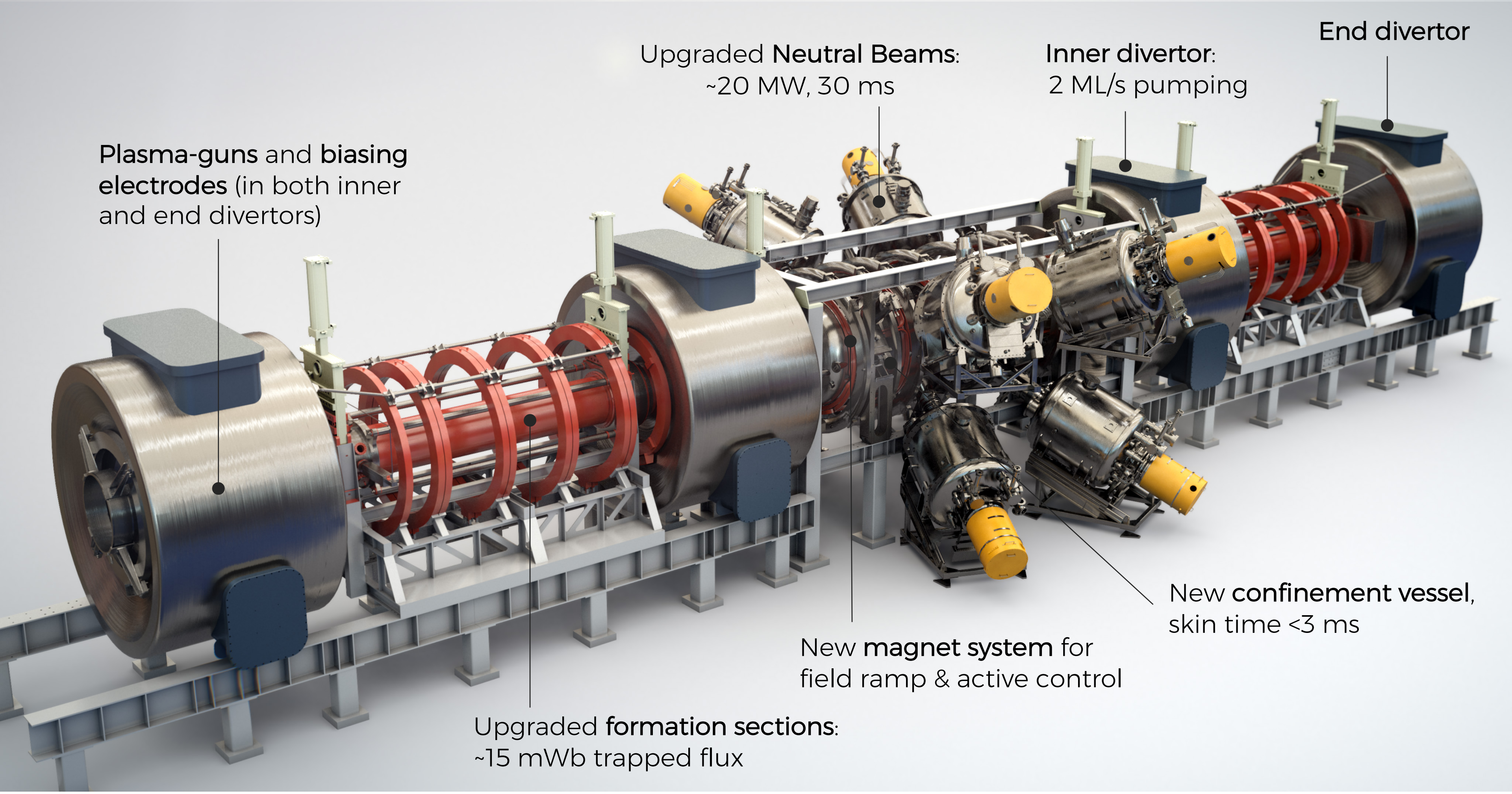
**C-2U – Sustainment 5+ ms**
1 kG, 1 keV
neutral beams, Wb ~100 kJ




(Radius normalized)

* HPF – High Performance FRC regime

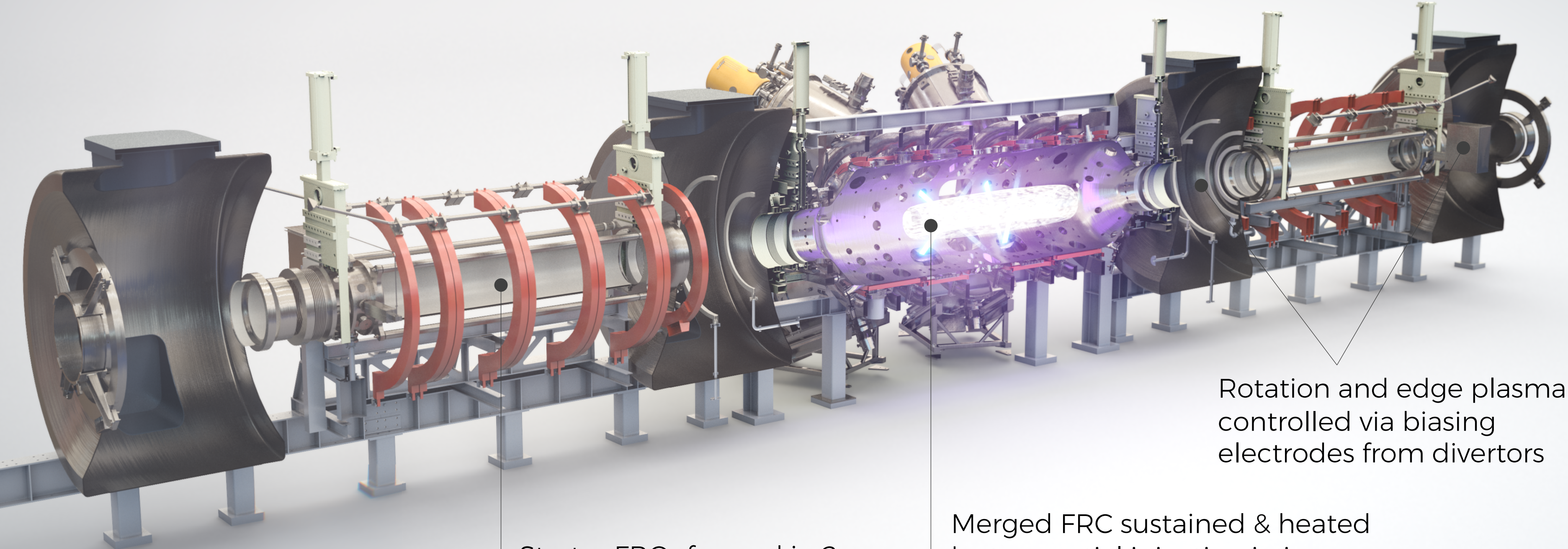
# NORMAN (C-2W) — current device




## Typical parameters:

| | | | |
|---|---|---|---|
| Magnetic field – $B_z$: | up to 0.3 T | Density – $n_e$: | $1\text{-}3\times10^{19}$ m$^{-3}$ |
| Plasma dimensions – $r_s$, $L_s$: | 0.4, 2-3 m | Temperature – $T_{tot}$: | ~3 keV |

# Experimental setup and key approaches




Key approaches to Norman experiments:

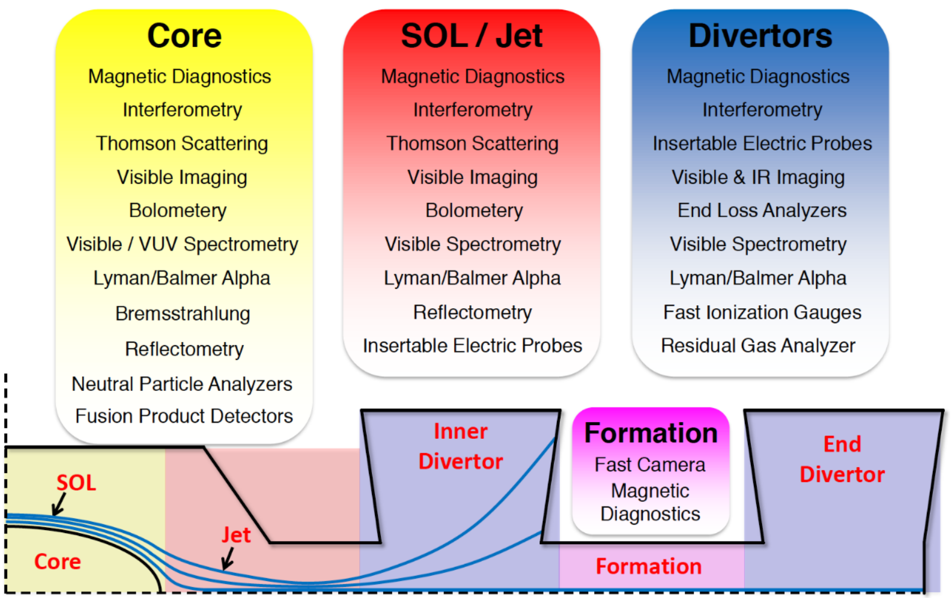
1. FRC dynamic formation
2. Boundary control via edge biasing
3. Neutral-beam injection
4. Wall conditioning
5. Particle refueling
6. Plasma shape/position control

# Sophisticated Norman diagnostic suite

**Four main zones of Norman have 60+ types of diagnostics:**

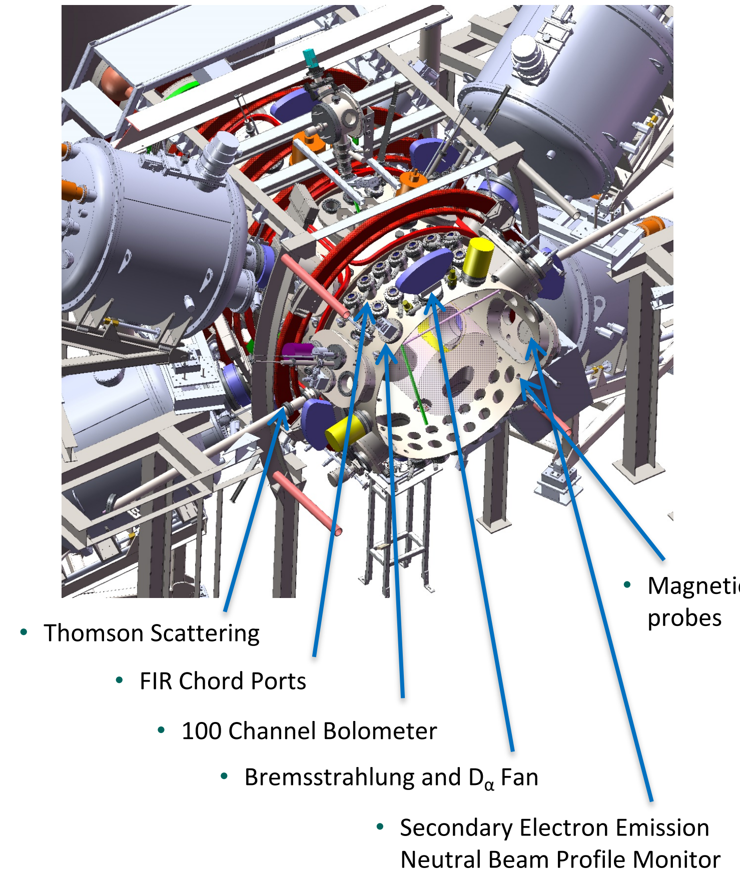
- Core plasma inside the FRC separatrix
- Open-field-line mirror-confined plasma in the scrape-off layer (SOL) and jet
- Rapidly expanding plasma in the inner divertors and/or end divertors
- FRC formation sections

Roche, et al., Rev. Sci. Instrum. 92, 033548 (2021)




Norman diagnostics by zones

Cross Section of C-2W Midplane

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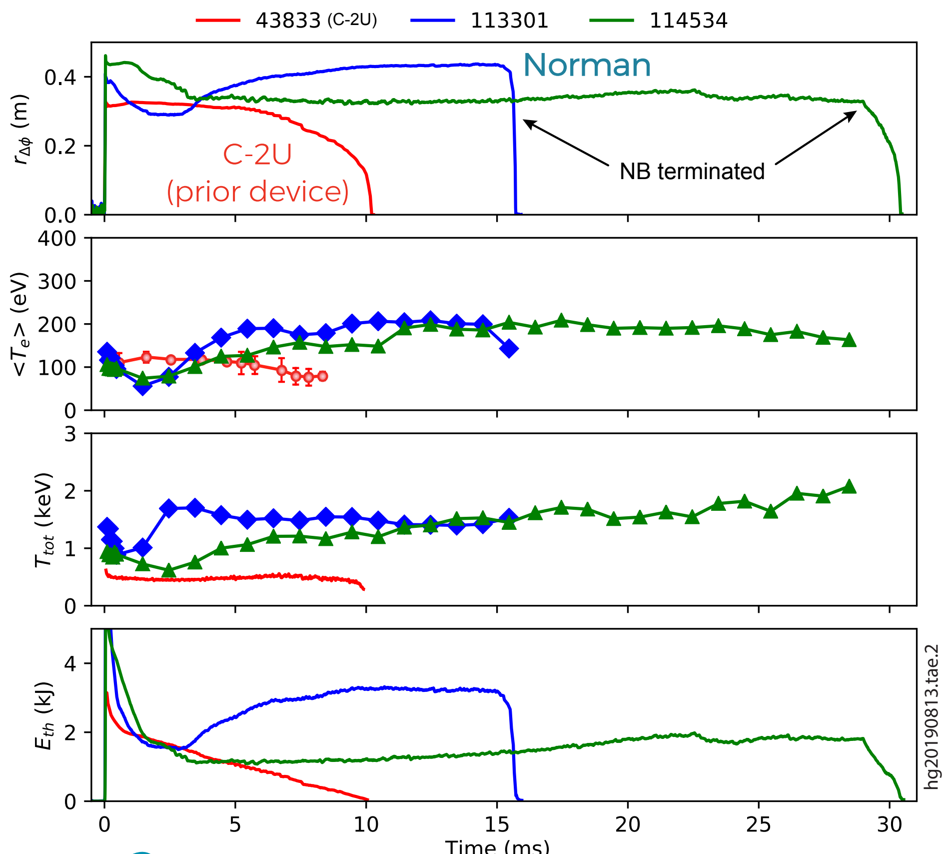
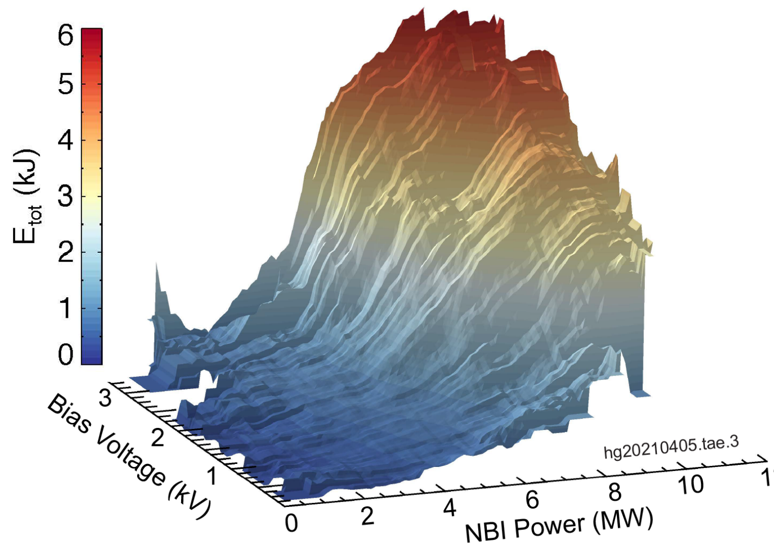
# FRC sustainment up to 30+ ms achieved in Norman

## Continuous optimization of FRC lifetime and ramping studies

- Compared to prior C-2U device
  - 3x longer plasma lifetime
  - 4-5x higher temperature
  - 4x higher plasma energy




- FRC performance well correlates with neutral-beam injection and edge biasing

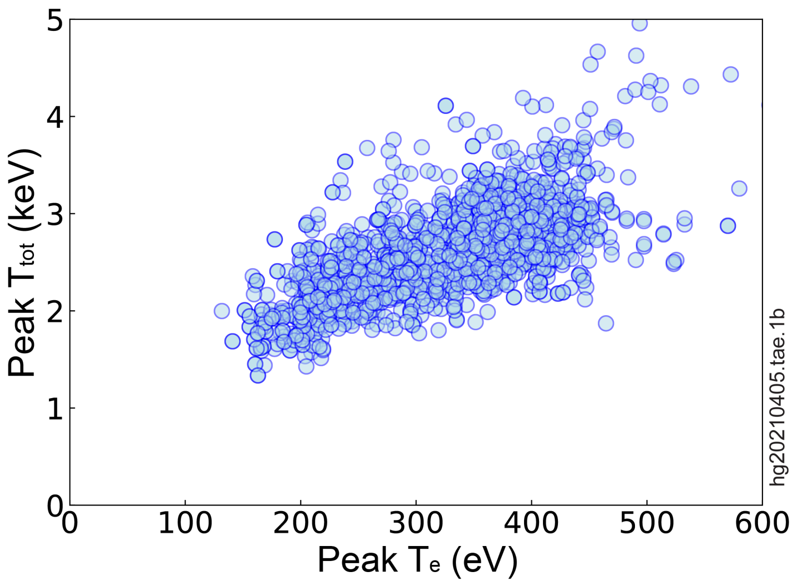



Plasma energy trend in Norman

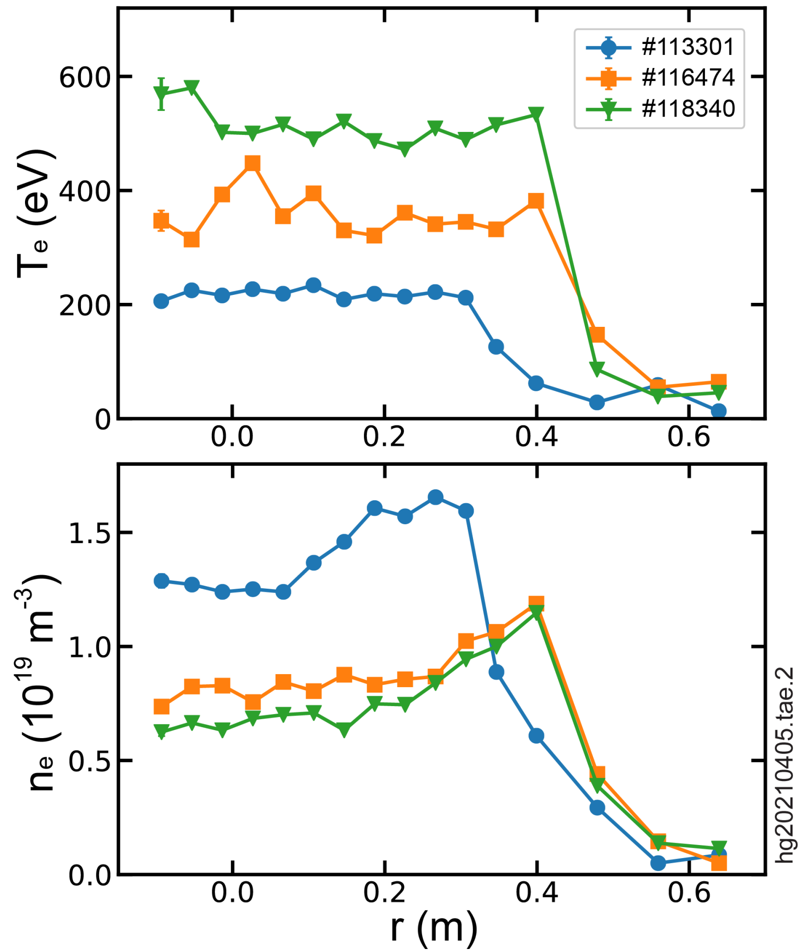
# High temperature FRCs achieved in Norman

## $T_e$ >0.5 keV, $T_{tot}$ >3 keV

- Norman can produce a wide range of $T_e$ & $n_e$: $T_e$ >0.5 keV (measured by Thomson scattering)
- Plasma temperature $T_{tot}$ >3 keV – estimated by interpretive plasma reconstruction using experimental measurements



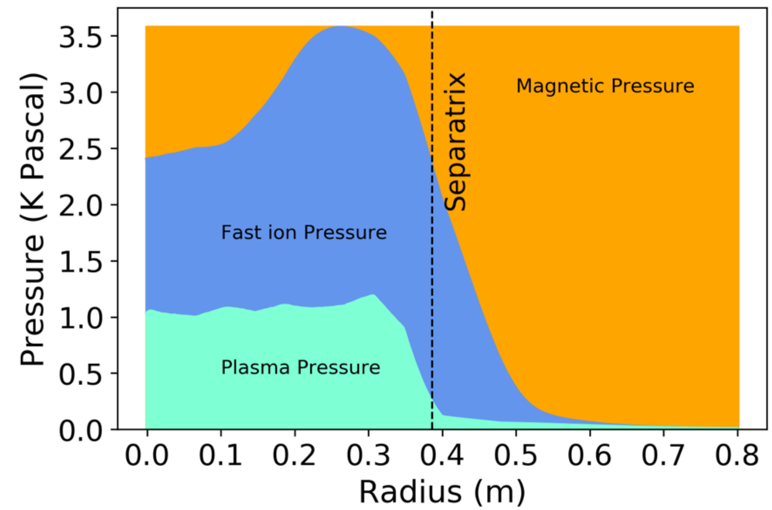

Electron temperature and density measurements by Thomson scattering (located at Norman midplane)



# Advanced beam-driven FRC enabled by fast ions

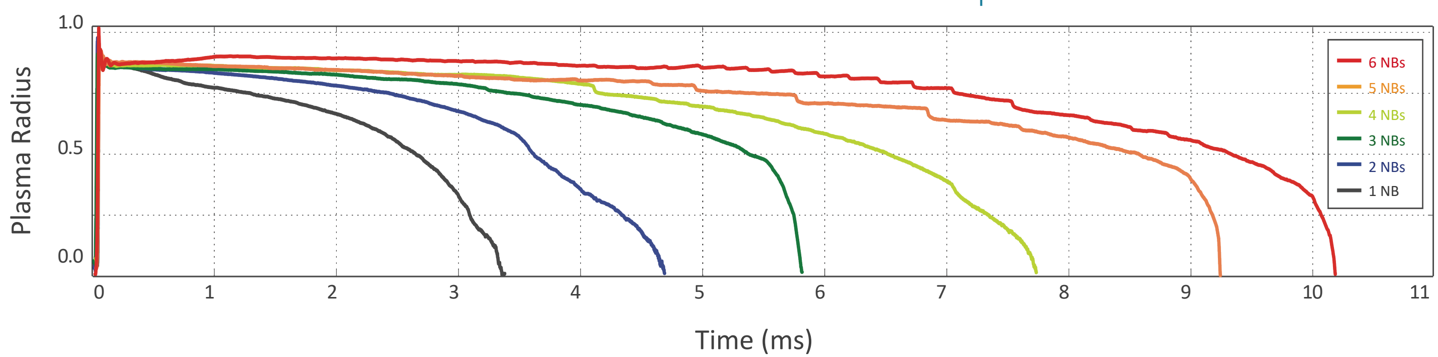
- Fast ion confinement near classical limit
- Total pressure is maintained, while thermal pressure is replaced by fast ion pressure, $P_{fast}/P_{th} > 1$ (from plasma reconstruction)
- Global modes are further suppressed
- Plasma lifetime increases with NBI power

Pressure profiles from interpretive plasma reconstruction




Gupta, et al., APS DPP2019

Plasma evolution with various NBI power

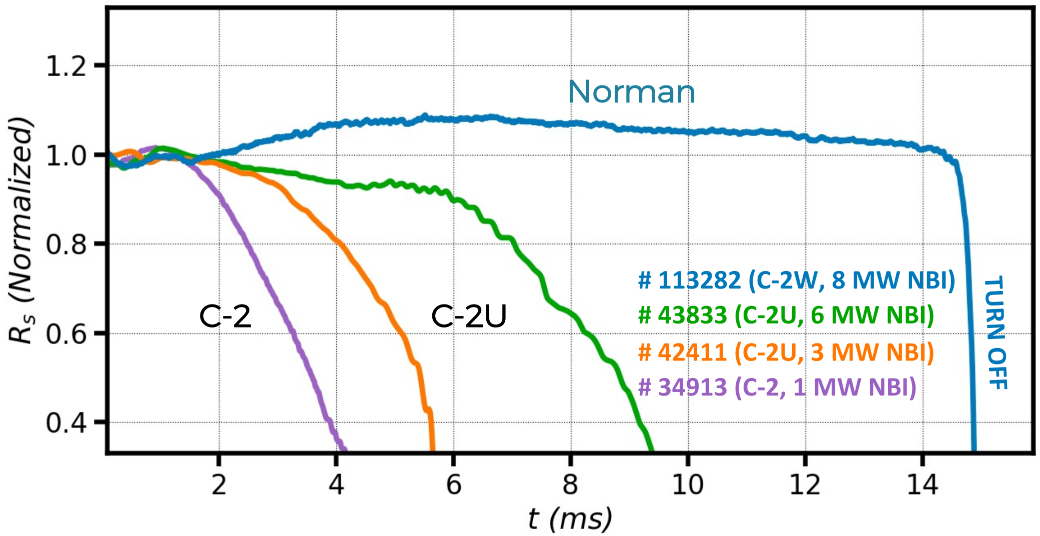


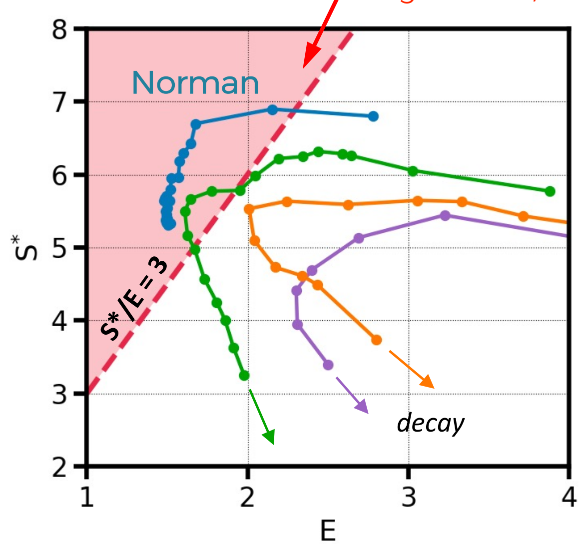

Binderbauer, et al., Phys. Plasmas 22, 056110 (2015)

# Demonstration of extending operational boundary

## Exceeding historical limit S*/E ~3 with substantial NBI power

- Kinetic parameter $S^* = r_s/(c/\omega_{pi})$: the ratio of separatrix radius to ion skin depth
- Empirically, keeping S*/E < 3 (E: plasma elongation) prevents FRC from tilting
- Norman demonstrated FRCs can exist and remain in S*/E > 3 region

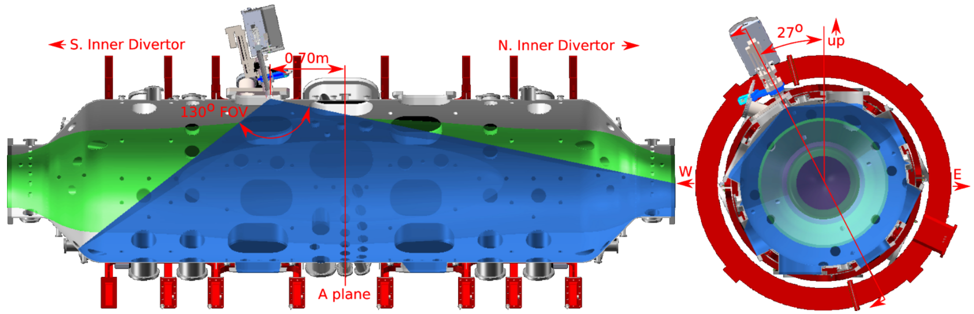


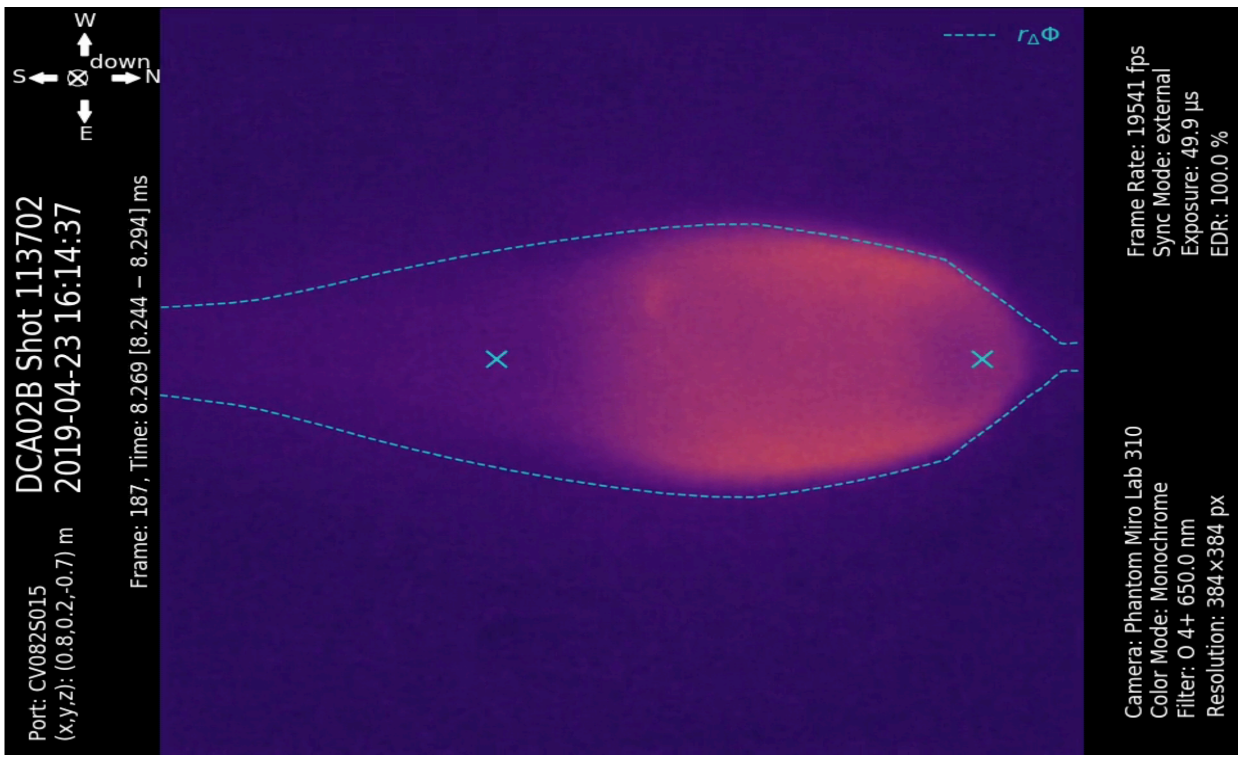



# Sustained plasma is stable and robust

## $O^{4+}$ radiation indicates hot electron zone and consistently tracks FRC radius

Fast-framing camera
(confinement vessel)



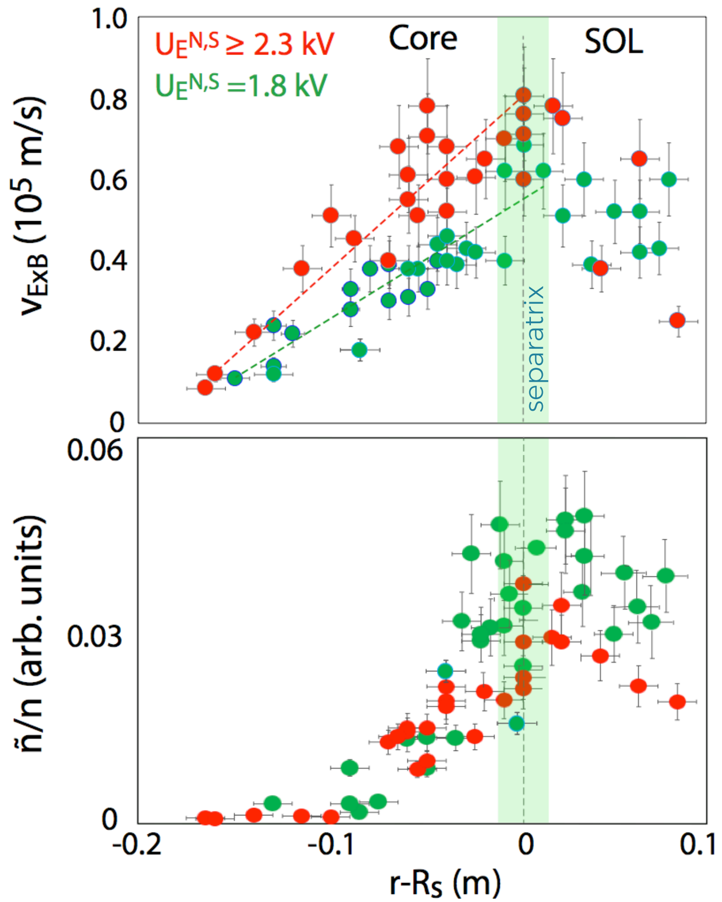

Granstedt, et al., Rev. Sci. Instrum. 92, 043515 (2021)

# Reduced density fluctuation level at higher edge biasing is consistent with increased ExB shear

- Strong E×B shearing rate ($\omega_{ExB}$) due to edge biasing from divertors
- Sheared E×B flow upshifts critical gradient and reduces turbulence via eddy shearing/decorrelation
- Radial transport barrier at/outside the separatrix
- Simulations confirmed ion-scale core stability and turbulence spreading (SOL to FRC core)

Lau, et al., Nucl. Fusion 59, 066018 (2019)

Doppler backscattering reflectometer measurements




Schmitz, et al., Nat. Comm. 7, 13860 (2016)

# Sophisticated plasma optimizations utilized

## Google's Optometrist Algorithm and in-house active control systems

- Plasma optimization via Google's Optometrist Algorithm routinely conducted
  - ➢ Produced breakthrough result by optimizing FRC formation parameters and other subsystems
  - ➢ Advanced algorithm with logistic regression

- In-house active plasma control systems routinely used as well

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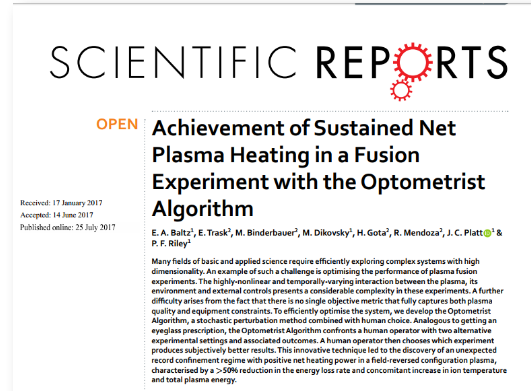

SCIENTIFIC REPORTS

OPEN **Achievement of Sustained Net Plasma Heating in a Fusion Experiment with the Optometrist Algorithm**

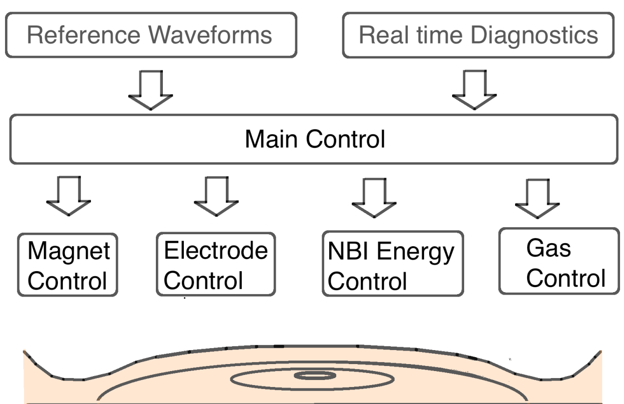
Received: 17 January 2017
Accepted: 14 June 2017
Published online: 25 July 2017

E. A. Baltz[1], E. Trask[2], M. Binderbauer[2], M. Dikovsky[1], H. Gota[2], R. Mendoza[2], J. C. Platt[1] & P. F. Riley[1]

Many fields of basic and applied science require efficiently exploring complex systems with high dimensionality. An example of such a challenge is optimising the performance of plasma fusion experiments. The highly-nonlinear and temporally-varying interaction between the plasma, its environment and external controls presents a considerable complexity in these experiments. A further difficulty arises from the fact that there is no single objective metric that fully captures both plasma quality and equipment constraints. To efficiently optimise the system, we develop the Optometrist Algorithm, a stochastic perturbation method combined with human choice. Analogous to getting an eyeglass prescription, the Optometrist Algorithm confronts a human operator with two alternative experimental settings and associated outcomes. A human operator then chooses which experiment produces subjectively better results. This innovative technique led to the discovery of an unexpected record confinement regime with positive net heating power in a field-reversed configuration plasma, characterised by a >50% reduction in the energy loss rate and concomitant increase in ion temperature and total plasma energy.

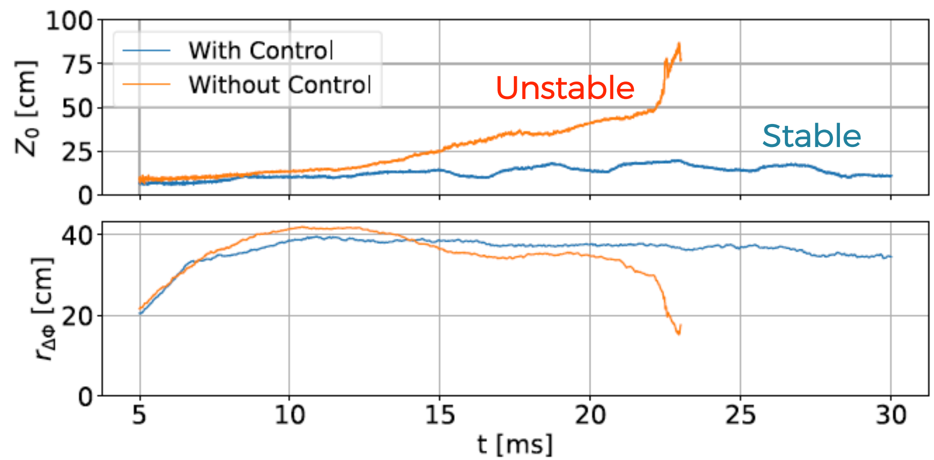
Baltz, et al., Scientific Reports 7, 6425 (2017)

### Schematics of active plasma control




Romero, et al., APS DPP2019

### Active control of FRC axial position



# Holistic data reconstruction through Bayesian inference

## Offers unique insights into internal plasma perturbations

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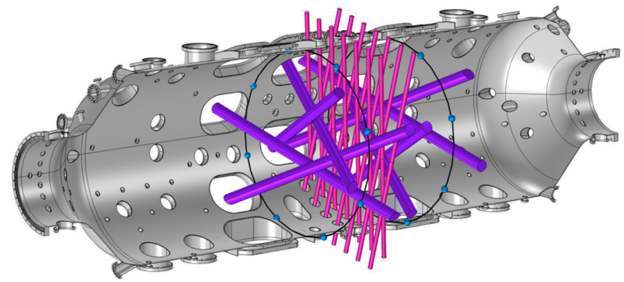
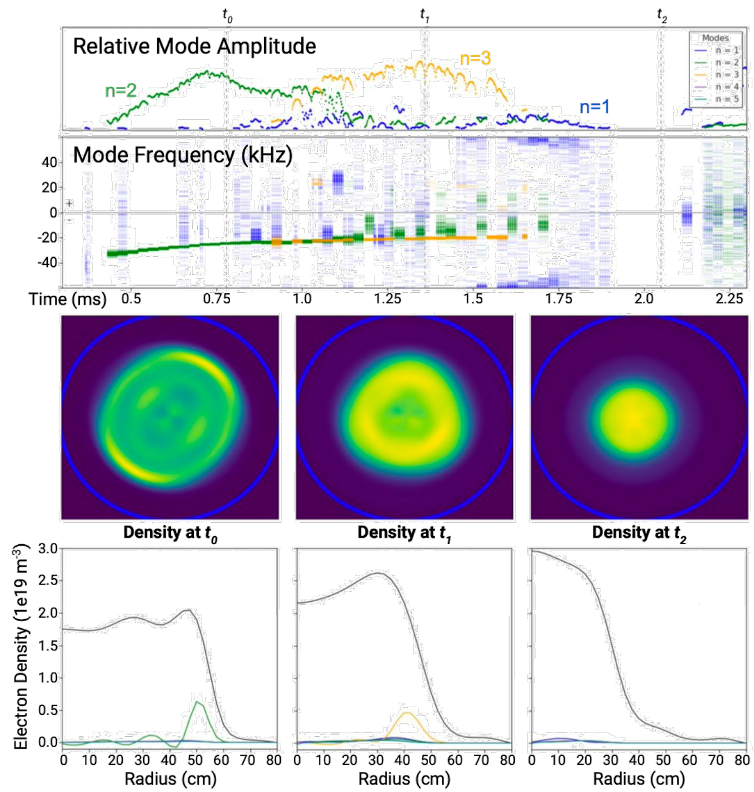
- FIR interferometry, Mirnov probes and Shine-Through diagnostics combined to enhance reconstructions
- Mode growth observed when NBI power reduced
- More diagnostics being integrated



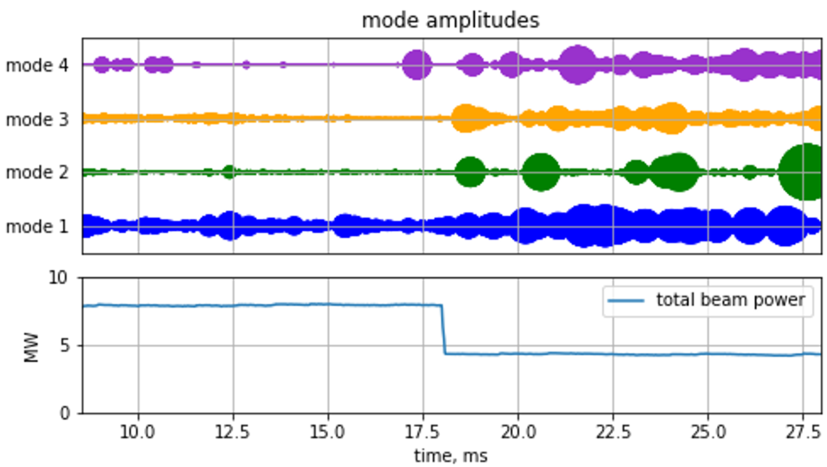



**Mode Amplitudes**
(color coded)

**Mode Frequency**
(same colors)

**2D Density Reconstructions**
(all modes)

**Mode Amplitudes**
(same colors)
(function of radius)

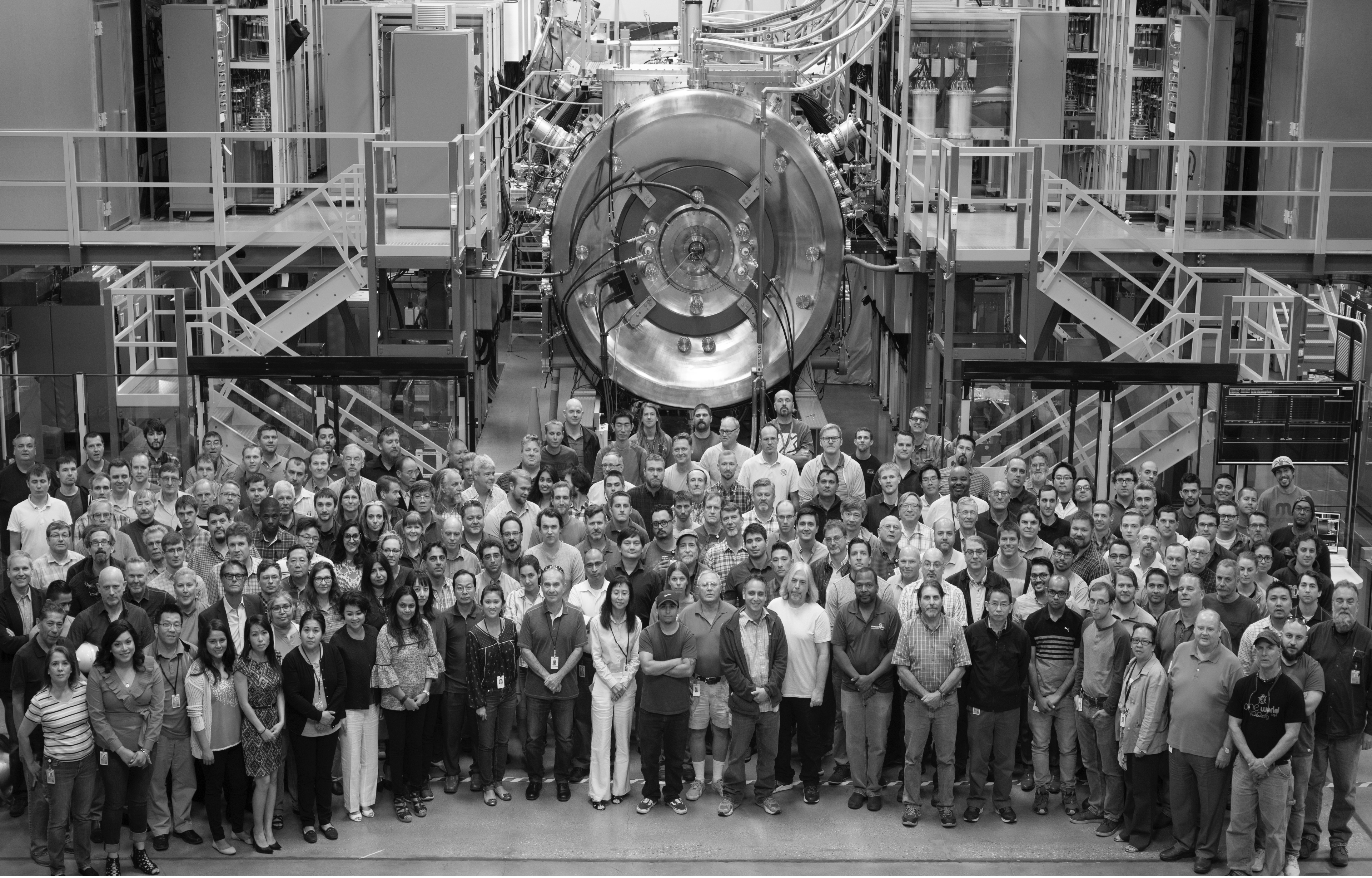



Dikovsky, et al., Phys. Plasmas (2021) in review

# Summary

- Demonstrated high-temperature FRC sustainment via neutral-beam injection and edge biasing up to 30 ms (limited by the energy storage on-site)
  - FRC performance well correlates with NBI and edge biasing
  - achieved "long enough" and "hot enough" ($T_{tot}$ >3 keV) milestones
  - extended operational boundary, S*/E >3, without tilting

- Advanced plasma and machine optimizations, through:
  - Optometrist Algorithm utilization (human + AI)
  - sophisticated active plasma controls on magnets, edge biasing, beams, and gas fueling.



# Thank You